Submilliampere threshold current pseudomorphic InGaAs/AlGaAs buried-heterostructure quantum well lasers grown by molecular beam epitaxy

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We report on low threshold current strained InGaAs/AlGaAs single quantum well lasers grown by molecular beam epitaxy. Broad-area threshold current densities of 114 A/cm^2 at 990 nm were measured for 1540-μm-long lasers. Threshold currents of 2.4 mA at 950 nm were obtained for an uncoated buried-heterostructure device with a 2-μm-wide stripe and 425-μm-long cavity. With reflective coatings the best device showed 0.9 mA threshold current ($L = 225\ \mu$m). Preliminary modulation measurements show bandwidths up to 5.5 GHz limited by the detector response.

The lattice-mismatched InGaAs/GaAs system has received considerable attention over recent years. As long as the thickness of the strained layer is below the critical value,[1] the difference in lattice constants between the materials will be accommodated by strain which can give rise to desirable material properties. The built-in strain, in the active region of a quantum well laser, can potentially lower the threshold current and increase the modulation bandwidth compared with conventional, lattice-matched, quantum well material.[2–4]

In this letter we report on buried-heterostructure strained InGaAs quantum well lasers with threshold currents (cw) of 2.4 and 0.9 mA for uncoated and coated lasers, respectively. To our knowledge this is the lowest figure reported to date for this material system and rivals the best results obtained in GaAs quantum well lasers.[5–7]

The sample was grown by molecular beam epitaxy (MBE) in a Riber 2300 R&D system and a schematic of the structure can be seen in Fig. 1. The laser consists of 1 μm n-GaAs buffer layer, 1.5 μm n-$Al_{0.5}Ga_{0.5}As$ cladding, 0.2 μm n^--$Al_xGa_{1-x}As$ graded (GRIN) region ($x = 0.5$–0.2), 40 Å GaAs spacer, 50 Å $In_yGa_{1-y}As$ quantum well, 40 Å GaAs spacer, 0.2 μm p^--$Al_xGa_{1-x}As$ GRIN ($x = 0.2$–0.5), 1.5 μm p-AlGaAs cladding, and 2000 Å p^+-GaAs cap layer. The structure was grown on GaAs (100) substrates tilted 4° towards (111)A and apart from the active region, it is identical in composition to the high quality GaAs quantum well lasers grown in our laboratory.[8] The substrate temperature was held at 600 °C for the GaAs buffer and cap layers, 720 °C in the cladding and graded regions, and ramped down to about 620 °C for the InGaAs quantum well. Temperatures quoted are pyrometer readings. Since the sticking coefficient of In is significantly less than unity at our substrate temperatures, it is difficult to accurately state the amount of In incorporated into the film.

After MBE growth, broad-area lasers ($w = 100\ \mu$m) were fabricated and tested. The lasing wavelength was 990 nm and a threshold current density of 114 A/cm^2 for a 1540-μm-long laser was determined under pulsed conditions. Internal quantum efficiencies near 0.6 and distributed losses of 9 cm^{-1} were typical for these devices.

To fabricate buried-heterostructure (BH) lasers, mesas with an active layer width of 2 μm were chemically etched. The top GaAs layer was removed immediately prior to loading into a liquid phase epitaxy (LPE) system for regrowth. During this process the temperature was 800 °C. After regrowth, the wafer was processed into BH lasers, using con-

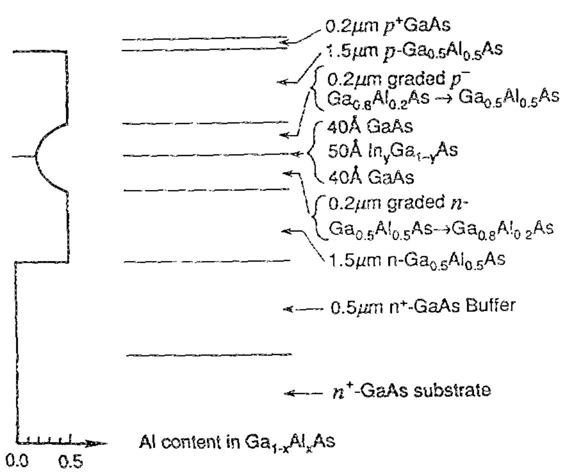

FIG. 1. Shows schematically the laser structure.

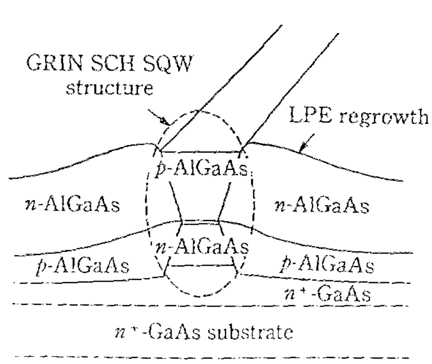

FIG. 2. Schematic diagram of the buried-heterostructure laser.

TABLE I. Threshold currents and corresponding cavity lengths for uncoated lasers.

Length (μm)	2960	1676	1004	425
I_{th} (mA)	11	5.6	4.2	2.4

ventional fabrication techniques. A schematic of the finished laser is shown in Fig. 2.

To test the performance of the devices, the wafer was subsequently cleaved into lasers bars of various cavity lengths. Light versus current curves were measured under dc conditions at room temperature, and very low threshold currents were observed. Some of the measured threshold currents along with their respective cavity lengths are listed in Table I. We see that the lowest threshold current density was 167 A/cm^2 for the 1676-μm-long cavity, which is less than a 50% increase over the broad-area lasers of nearly the same cavity length. We notice a shift in lasing wavelength to 950 nm for the BH lasers which we attribute to mixing of the GaAs spacers and the InGaAs quantum well during the high-temperature cycle in the LPE furnace. Other groups have reported similar observations.[9]

It can be seen from Table I that the lasing threshold current has a weak dependence on cavity length which indicates very low internal losses within the laser. Based on this observation, high-reflectivity dielectric coatings were applied to the laser mirrors and considerable reduction in threshold current was realized. Our best results correspond to threshold currents as low as 0.9 mA measured in lasers ($L = 225$ μm) coated to give reflectivities of $R1 \approx R2 \approx 0.85$. Figure 3 shows the light-current characteristic of a laser ($L = 425$ μm) prior to and following coating. The laser with 1 mA threshold is able to deliver cw optical power greater than 5 mW per facet with a slope efficiency of 0.22 mW/mA, which is a consequence of the low internal losses.

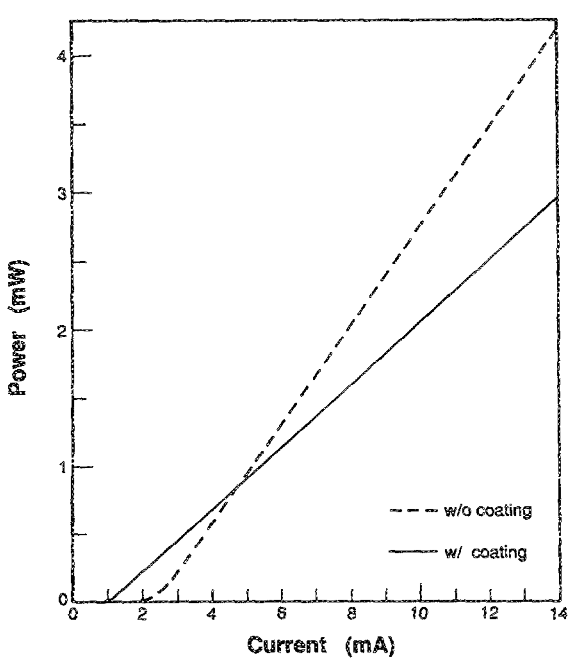

FIG. 3. Light output vs current for a 425-μm-long buried laser with and without high-reflectivity coatings.

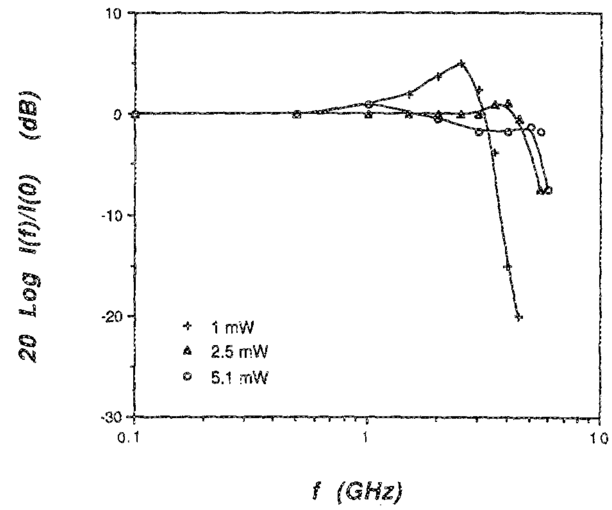

FIG. 4. Modulation response for output power levels of 1, 2.5, and 5.1 mW.

We also tested these lasers for high-frequency modulation using an InGaAsP photodiode as a detector. The frequency response of the laser is shown in Fig. 4 for power levels of 1, 2.5, and 5 mW. A maximum bandwidth of 5.5 GHz was observed which is comparable to GaAs BH laser performance at similar power levels. However, we are currently limited by our detector response so that the response of the InGaAs lasers extends to even higher frequencies. More complete modulation data will be presented at a later date.

In summary, we have fabricated BH lasers from strained InGaAs quantum well material with threshold currents of 2.4 and 0.9 mA for uncoated and coated lasers, respectively, possessing very low internal losses. These results are more than a factor of 2 less than previously obtained for these materials and are as good as those of lattice-matched GaAs uncoated quantum well lasers.

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